

CONTACT BINARY STARS IN MICROLENSING SURVEYS

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Abstract

A brief summary of properties of the contact binaries is presented, with the goal to stress the unsolved problems of their formation and evolution as well as their potential contribution to studies of Galactic stellar populations. The first results from the OGLE survey, where the contact binaries contribute a full two thirds among 933 eclipsing binary stars, are presented.

1 Properties of contact binaries

1.1 What are contact binaries?

This review summarizes essential information about the contact binary stars (this Section) and gives a brief, initial report on the results for the contact binaries in the OGLE sample (the second part of this review). Several reviews have written about the contact binaries. The most recent ones, with respective stress on observations and theory, were presented by Eggleton [8] and Rucinski [32]. Most issues signaled, but not fully expanded here, should have been covered in these two reviews, which also list the previous contributions.

A contact binary is one star with two mass concentrations. It is described reasonably well by the Roche model (Fig. 1). This model assumes synchronous orbital motion and rotation of weight-less matter attracted by two mass centres. The synchronous rotation has never been demonstrated for contact systems, but there exist arguments that it should be at least approximately valid, especially for highly convective envelopes where strong interaction of eddies should lead to an efficient transport of angular momentum. According to some predictions [1], the external appearance of contact binaries should be exceedingly simple, as of a wooden model of a uniformly-painted common Roche equipotential.

It is customary to divide contact binaries into the *W UMa-type* systems with periods shorter than about one day and *long-period* or *early-type* contact systems consisting of massive stars and orbiting on much larger orbits with periods of the order of a couple of days. It is not clear if this grouping is entirely due to the observing time-gap at one day, or maybe reflects deep-rooted differences in structure. The catalogue data are heavily biased by various selection effects and one of the most important goals of the micro-lensing databases might be to establish a bias-free statistics in the period domain. We will concentrate on the *W UMa-type* systems, also frequently designated as the *EW* variables.

The light curves were the only source of information for long time. Obviously, they compress the 3-D geometrical and atmospheric information into a 1-D time-variability function. Only recently some preliminary data have been obtained using moderate-to-high resolution spectroscopy, which provides information resolved in one coordinate. This is because with solid-body rotation and revolution of the contact structure, the radial-velocity coordinate can be identified with the projected distance from the rotation axis ([17] [30] [39]).

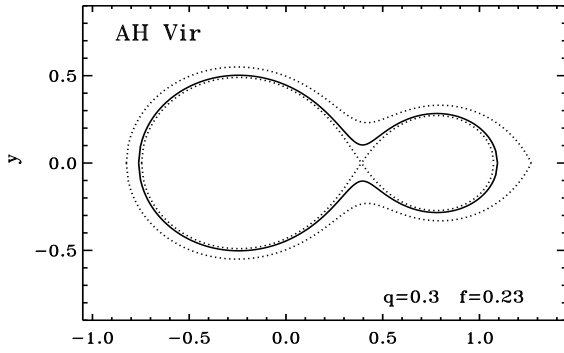


Figure 1. The equipotentials for AH Vir, whose light curve is shown in the next figure. Light curves generated with the assumption of simple geometrical variability of the radiating area are in perfect agreement with the observations. However, the information content of the light curves is low, with the mass-ratio being the most difficult parameter to find.

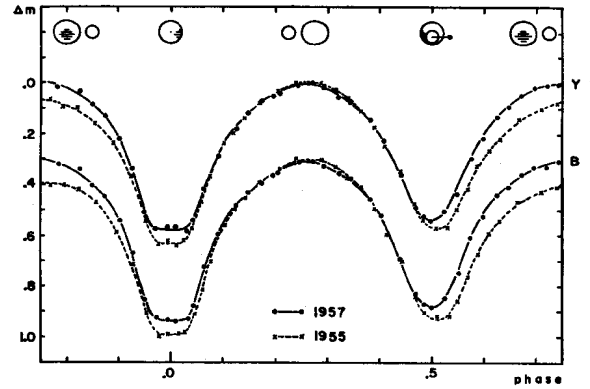


Figure 2. The light curves of AH Vir obtained by Binnendijk in 1955 and 1957 [3]. Contemporary light curves do not look much different than these old observations, but the interpretation is entirely different. Modern spectroscopic observations of AH Vir are in [17].

The contact model based on the common envelope joining both stars and forming just one structure dates back to the late 1960's, since the time of the seminal papers of Lucy [18] [19] [20]. Before these papers, the light curves were interpreted as resulting from eclipses and distortions of detached but very close binaries, because the “normal” (i.e. relatively strong) dependence of the surface brightness on the local gravity (the von Zeipel law) usually implied moderate distortion (Fig. 2). Several points were quite mysterious: Why this distortion would be so similar for so many eclipsing binaries? What would prevent systems from expanding even more? The “Lucy” model solved these problems. It also explained the following strange property:

First spectroscopic results in the 1950's and later showed that masses of the two centres usually differed very appreciably, typically in the ratio 1:3 or so. The contact binaries were known to be more-or-less Main Sequence stars (some have visual companions; a few are near enough for trigonometric parallaxes). Then, the luminosities should scale in the ratio of about $1:3^4$ or $1:3^5$, whereas they seemed to scale simply linearly with masses. In the same time, this whole group of eclipsing stars is known to show eclipses of similar depths of eclipses, implying identical surface temperatures, in spite of usually strongly differing masses. Something must be very different here than in normal stars.

The great ideas of Lucy resolved both problems: He argued that for convective stars the gravity darkening is weaker, so that – to explain the curved light maxima – the distortions can be stronger, as strong as the physical contact. Once the contact is established and effectively one star is formed, the energy can flow freely and can equalize the effective temperatures. The luminosities scale as radiating areas which, for the Roche geometry, scale as masses in the first power. This leads to a working definition of a contact binary: a close binary whose masses are different, yet effective temperature is more or less the same everywhere. Analyses of the light curves as well as the broadening functions fully confirm that model. Small deviations from this simple model can be explained by stellar spots, which are entirely expected on late-type, rapidly-rotating stars. There exist also systematic deviations from this definition related to the so-called A/W dichotomy and to poor thermal contact in some systems, but we will not discuss those relatively minor complications here.

1.2 Structure of contact binaries

Contact binaries seem to be on, or close to, the Main Sequence. Some show signatures of a mildly evolved state when they are slightly bigger and cooler than the others of the same masses. They do not appear among giants. While their external appearance is simple, the structure is known very crudely. The original assumption of Lucy that they must have turbulent convective envelopes seems to be too restrictive because the contact binaries do appear in large numbers not only among late-type

stars (later than middle A-type), but they are present also among O-type Main Sequence stars which should not have any appreciable outer convection zones. Thus, the turbulent convection is not the necessary condition for establishing a good thermal contact which leads to equalization of the effective temperatures. We should however note, that lack of contact binaries among B-type MS has been signaled, although always with a recognition that it might be due to severe selection effects against discovery for periods close to 1-2 day. It should be noted that B-type contact systems seem to exist in the EROS sample [11].

The crucial point in understanding of the structure is related to the mechanism of the energy transfer. Possibly, the turbulent convection is not the only possible means for transporting the energy between components. But we must remember that huge amounts of energy are involved. Usually, for the less-massive component in a contact system, the energy received from its more-massive companion exceeds its own nuclear energy by a large margin. At present, we have no idea how is this energy transported between the stars. And it is definitely not easy to move it there, as the flow vector must be, on the average, perpendicular to the gravity vector (the latter coincides with the direction of convective elements motions). Whatever is the energy transfer, one property of contact binaries is clear: They must consist of dissimilar (non-homologous) components. The original models of Lucy encountered problems with explaining the whole range of masses and periods because (almost) homologous ZAMS stars were assumed. All subsequent models were aimed at explaining the whole range of observed periods and colours. The PC relation, which we briefly describe in the next section, was especially useful here.

Components of contact systems exchange not only energy but also mass. Considerations of the thermal stability by Lucy[21], Flannery[9], Robertson & Eggleton[28] led to a clear conclusion: The contact configuration is unstable and evolves in the thermal time-scale of the less-massive component towards decrease of the mass-ratio. With preserved angular momentum, this should lead to an increase in the orbit separation and thus to the disruption of contact. But then, the nuclear evolution of the primary should lead to its expansion and a somewhat faster re-establishment of the contact. The Thermal Relaxation Oscillations (TRO) were suggested to describe this phenomenon. But is the angular momentum of the orbit really constant? We return to this in Sec. 1.5.

1.3 The period-colour relation.

The relation between the period and color (PC), observationally established by Eggen [6] [7], plays a special role in studies of W UMa-type systems. Its essence is that the contact binaries are only moderately evolved so that even a loose mass-radius relation, coupled with the topologically same contact geometry, must lead to a sequence relating sizes of stars (measured by orbital periods) to their effective temperatures (measured by the colours). At the red end, there are small, short-period systems; at the blue end, there are big, long-period systems. For the W UMa systems, the range in periods is between about quarter of a day, and one day where the spectral sequence goes from early-K to middle-A spectral types. The short-period end is very well defined: Contact binaries do not exist with periods below 0.22 days. At the hot end, the colours stop changing with effective temperatures and the PC relation becomes poorly defined. This is due to the evolution, which affects mostly more massive systems. Generally, the PC relation is only moderately tight as it reflects evolution of some contact systems leading to longer periods and redder colors for more evolved systems.

One property should attract our attention at this point: The short-period/blue envelope of the PC relation (Fig. 3). It is particularly important as it is expected to be well defined, being delineated by the least-evolved systems. Differences in metallicities enter here and might affect the colors, so that use of metallicity-insensitive colours is especially important. For example, the $V - I$ colour is relatively insensitive to variations in metallicity, $\Delta(V - I) \propto +0.04 [Fe/H]$ [36]. However, large effects can be expected for strongly metal-deficient systems observed with metallicity-sensitive colours, such as $B - V$ [34]. The short-period/blue envelope in Fig. 3 has been approximated by a simple relation: $V - I = 0.053 P^{-2.1}$, with the period P in days.

1.4 Activity of contact binaries

Contact binaries have very short orbital periods, of the order of a small fraction of a day. When spectral types are later than early-F, convective envelopes are expected. With rapid rotation, this should lead to solar-type activity. Indeed, we observe very strong photospheric (spots), chromospheric (UV and EUV line emission) and coronal manifestations of this activity for the W UMa-type systems. Because of the PC relation, systems with later types rotate more rapidly than those with earlier spectral types. This is contrary to what we normally see among field stars which rotate – on the average – more slowly with more advanced spectral type. There are many unsolved problems here: Why contact systems seem to be less active than extension of period-activity relations for short-period detached would suggest? Are somewhat erratic period changes observed in W UMa systems related to magnetic activity, or do they result from instabilities in the energy/mass transfer? Why some systems seem to be more active than the other? Is activity the main underlying reason for several other peculiarities observed in contact systems, among them the systematic deviations from the expected surface-brightness distribution (the A/W dichotomy)?

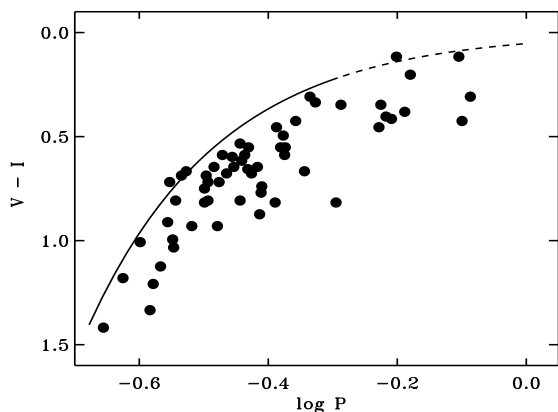


Figure 3. The period–colour diagram for the nearby field systems, established for the data from the compilation of Mochnacki [24], and transformed to the $V - I$ colour.

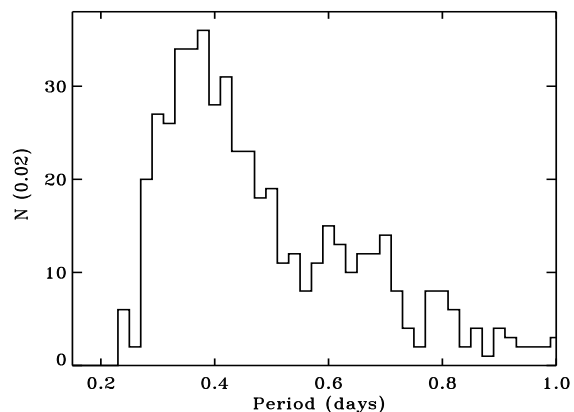


Figure 4. The period distribution for field contact binaries [31].

For the general picture, the most important is just the very fact of strong magnetic activity. We know that magnetized winds lead to angular momentum loss (AML) from individual stars. In contact systems, with practically perfect synchronization, this will extract angular momentum from the orbit. The orbit will shrink leading to an eventual coalescence. The contact stage would be then just a stage in the evolution from binary to single stars. Does this stage last long since we see so many contact systems?

1.5 How do they form and evolve?

Initially, attempts were made to model zero-age MS contact binaries as they would be easiest to calculate. But all observations point to them being moderately old. This conclusion is based on the presence in old open clusters and in globular clusters. No single W UMa-type binary has been discovered in a young cluster. The early-type contact systems do exist in young associations, but are they really age-zero, in the sense of not being evolved at all?

Spatial motions of contact binaries were studied by Guinan & Bradstreet [12]. They found that spatial velocities are quite large and most similar to Old Disk population. There exist no data on metallicities of contact systems as they have extremely broadened spectra. The *uvby* colours seem to indicate some weak correlation of UV excesses with spatial velocities, but this is confused by intrinsic chromospheric activity.

The current paradigm sees contact systems as an intermediate stage in the never-ending process of angular momentum loss which starts with formation of binary systems from molecular clouds and

continues through all stages of stellar evolution. The picture has been developed with many authors contributing here (in particular: [12] [41] [45] [46]). In this picture, close, but detached binaries would slowly lose orbital angular momentum through the magnetic wind and tidal coupling, while simultaneously evolving nuclearly. This process does not have to be as rapid (or accelerating at later stages) as initially thought, if the activity and AML are “saturated” at high rotation rates [41]. If this process is slow, then we might have many contact binaries. But it is exceedingly difficult to make any predictions here, as the initial frequency of detached binaries, efficiency of the AML and of the tidal coupling enter here. Then, we have no idea how the process of coalescence really happens: Is this through some sort of mass-exchange? How quickly would a contact system emerge from this process? Would the result look like a Blue Straggler? To what extent would the result depend on the nuclear evolution of the components?

It seems that another process can contribute to formation of contact systems. It cannot be the main mechanism as relatively large stellar densities are needed. As pointed out by Leonard and collaborators ([15] [16]), collisions of wide binaries in cores of stellar clusters have relatively high probability of occurrence, as sizes of orbits rather than sizes of individual stars are of importance here. After a dance of four stars, usually one star is ejected, but three form a hierarchical system with one very close binary.

1.6 Observations of field contact binaries

We know over half a thousand contact binaries, but the data are extremely inhomogeneous and subject to very strong selection biases. Good good photometric data exist for some 130 systems, but only for half of that in standard photometric systems. Thus, there have been many solutions of light curves, some spectroscopic determinations of radial-velocity orbits, but a coherent picture is not yet available. Even some crucial questions which could really help in resolving problems listed above cannot be answered at this point. The three which I consider the most important now and which are still unresolved are:

How many contact binaries are out there? Careful analysis of known contact binaries by Duerbeck[4] suggests the apparent frequency of about one such a system per 1000 normal stars, which agrees with simple counting of stars in the sky [32]. But comparison of variability amplitudes for these sky-field systems with surveys of old open clusters reveals that low-amplitude variables are under-represented in the former sample ([13] [38]). Even after elimination of background and foreground systems from the cluster samples, the apparent frequency is definitely high, perhaps about 1/300, leading to the spatial frequency (corrected for undetected low-inclination systems) as high as 1/150 [33], both for systems which are in the old open clusters as well as for those which seem to be just Milky Way projections.

What is the distribution of orbital periods? So far, such a distribution could be formed only for the sky-field sample, as there are still too few systems in clusters (and these clusters differ too much between themselves). The distribution at long periods might reflect all sort of selection biases, but the short-period cutoff at about 0.22 day is definitely real (Figure 4). What causes it? Is it really the full-convection constraint ([31]) which prevents formation of less-massive, cooler contact systems?

What is the distribution of mass-ratios? This crucial question cannot be easily answered without massive spectroscopic observations, and these are slow to come as they require considerable amounts of large telescope time (exposures must be short because of the radial-velocity smearing). Multi-aperture spectrographs would help, although such observations would not be easy, requiring resolutions of about 10 – 20 km/s, which is rarely seen in multi-slit systems. Quite another approach would be via statistics of variability amplitudes, through an inversion the equation mapping the mass-ratio distribution, $N(q)$, into the amplitude distribution, $n(a)$, which has the form: $n(a) = \int K(q, a) N(q) dq$. With calculated values of the kernel $K(q, a)$, this relation could be inverted, but would require a very good knowledge of $n(a)$, which could come only from large statistics of contact systems.

1.7 Observations of systems in stellar clusters

Some 15 years ago only half a dozen W UMa systems were known in stellar clusters: 4 systems in NGC 188, one in Praesepe, one in M67. Recently, mostly through the extensive work of Janusz Kaluzny and collaborators, the list is quite extensive and contains almost one hundred systems ([13] [38]).

Why clusters data are useful? They permit to study relative frequency of occurrence, as samples are well defined and membership can be established, partly by sky position coincidences, but preferably by proper-motion studies. For cluster members, we can relate and order the contact systems in age and metallicity sequences. We can also place the systems relative to the colour-magnitude diagrams and obtain some insight into their evolutionary state. Finally, having the colour, period and absolute-magnitude data, we can establish a mutual relation, which can help in weeding out non-members from data for further clusters. Such an absolute-magnitude calibration [33] uses very simple geometrical principles: the period scales with size of the system, while the colour scales with its surface temperature; both are linked to the total luminosity.

The essential results for open clusters ([13] [38]) are: Most systems appear in old clusters, with single systems in relatively young clusters such as Be 33 (0.7 Gyr) or Praesepe (0.9 Gyr). Then the numbers increase, to as many as more than a dozen members (among 28 discovered) in the populous old cluster Cr 261. Most systems seem to be located close on the Main Sequence, in the vicinity of the Turn-Off-Point. Although several Blue Stragglers were suspected in the old open clusters, most of them seem to be foreground projections. A few mild BS's might be there, however. The lower parts of the Main Sequences seem to give fewer detections, with a normal suspicion that searches are less accurate there. But maybe they are really missing? There exists after all the short-period cutoff of the period distribution, which through the PC relation should give a colour cutoff as well.

The essential results for globular clusters: So far, only low- and moderate-concentration globular clusters have been accessible from the ground. The picture is far from being a simple one. First W UMa systems in globular clusters were found with surprisingly high frequency among Blue Stragglers ([22] [23]), but recently Yan & Mateo [47] discovered them also below the TOP (but above and along the MS) in M71. Observational selection effects are formidable below the TOP in globular clusters in most cases so that it would be premature to conclude that the MS contact systems do not exist there. However, the first data from the Hubble Telescope ([29] [5]) indicate that globular clusters might, indeed, be deficient in Main Sequence contact systems and the frequency might be as low as 1/3000. This can be explained by destruction of contact systems, either by collisions or by the continuing AML.

2 Preliminary results for one survey: the OGLE sample

2.1 The main reasons

The contact binaries are simple. The complex physics takes place inside them, but externally they are not complicated. They are in fact almost as simple (externally!) as radially pulsating stars and can be described by fewer parameters than detached binaries: one common equipotential instead of two independent radii, an almost identical temperature everywhere instead of two temperatures. (True, the mass-ratio remains and is difficult to determine). They are probably less good standard candles than RR Lyrae stars, mostly because of the relatively strong color dependence. Depending on the combination of the color and period, the absolute magnitudes for contact binaries can be estimated to 0.2 – 0.5 mag. The spread for the RR Lyrae stars of a given metallicity is some 2 – 4 times smaller, but this advantage is simply due to their occurrence in a very small region of the stellar parameter space. In this respect, the contact binaries have a great advantage: They occur with very high frequency. In the solar neighborhood, they are some 24,000 more common than RR Lyr stars!

The other reason why we want to study the contact binaries is that they have apparently formed, in their majority, from detached binaries. Thus, they retain the record of binary frequency in the

old population. This record is quite confused by transformations taking place at the time of contact formation, but still available through statistics of numbers of systems before, in and after contact. Basically, all statistics could be used here, but we need large samples, free of detection and observation biases (or at least with known biases). In this respect, the micro-lens surveys are an ideal tool. For the first time, we have statistically sound data for the variable stars.

2.2 The OGLE sample

The OGLE sample ([42] [43] [44]) has been analysed – so far – only in terms of time-independent quantities, quite as one would handle, say, an RR Lyrae database, without looking at individual light curves. The detailed account will appear elsewhere [37]; here we present only the essential results.

There are 933 eclipsing systems in the nine Baade’s Window fields. The data available are modest: the epoch 2000 coordinates, I_{max} magnitudes, $(V - I)_{max}$ colours, ΔI , the period and zero epoch, and the light curve (typically 100 – 190 points) in I . The sample contains systems with $14 < I < 18$, with indications that it is complete for amplitudes $\Delta I > 0.3$. Typical error per observation is about 0.02.

The OGLE project classified the eclipsing light curves visually. There were 604 contact systems with periods shorter than one day which had $V - I$ data available. An automatic classifier (Figure 5) has been constructed on the basis of the Fourier decomposition of light curves to avoid subjectivity of visual classification and to weed out poorly-observed systems. Contact binaries have very simple light curves, with typically only two even coefficients, a_2 and a_4 needed to describe them adequately. Detached binaries need more coefficients and show systematically different values for the (a_2, a_4) pair. In the representation: $l(\theta) = \sum_{i=0}^4 a_i \cos 2\pi i\theta$, with light $l(\theta)$ normalized at maxima; both even coefficients are negative. A theoretical line dividing contact and detached systems is expected at $a_4 = a_2(0.125 - a_2)$. The classifier is not only useful in automatic separation of contact (EW) and detached binaries (EA, E), but is also effective in rejection of pulsating stars. It has led to selection of 388 systems with well-defined light curves, the so-called “restricted” (R) sample.

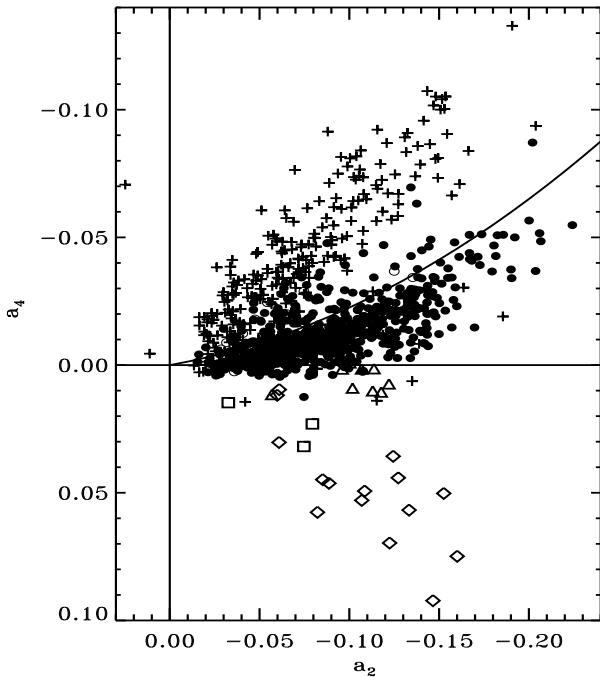


Figure 5. The dense “cloud” of contact binaries is easy to distinguish from other eclipsing stars (crosses) or from pulsating stars (open symbols, for various classes of RR Lyr and SX Phe).

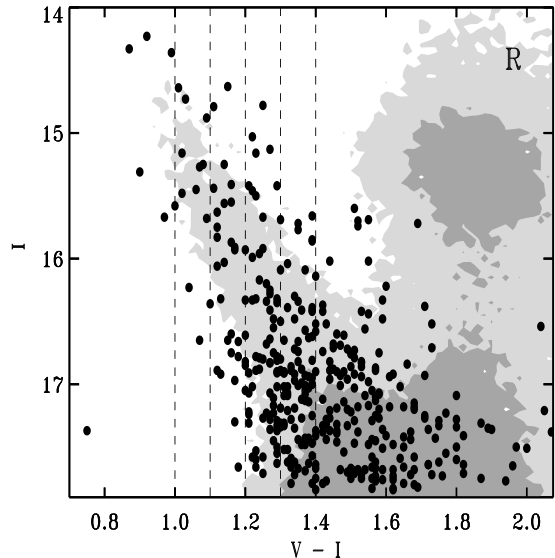


Figure 6. The colour-magnitude diagram for the OGLE sample [26]. The density of normal stars is shown by the grey area: light and dark grey correspond to 10 and 40 stars per cells of $\Delta I = 0.05$ and $\Delta(V - I) = 0.02$. The vertical lines delineate cuts where numbers of contact binaries were compared with numbers of normal stars (not discussed here).

2.3 The essential results

W UMa systems in the R-sample are shown together with a schematic outline of the location of the majority of stars in the OGLE fields [26] in the colour-magnitude diagram in Figure 6. There are good reasons to interpret the slanted band of relatively blue stars (cf. paper by Paczynski in this book; [2] [14] [25]) as a sequence formed by old, Turn-Off-Point stars, progressively reddened with distance. As we can see in the figure, the contact binaries scatter around this sequence, indicating a common origin. We note that the line of sight points at the Galactic Bulge, some 560 pc from the Galactic Centre, so that we see apparently disk stars, but at relatively large distances from the plane. We have a clear and direct indication that the contact systems belong to an old galactic disk population.

Having the orbital periods and colours, one can determine the distances using a $M_I = M_I(\log P, V-I)$ calibration ([33] [35] [36]). In the direction of the Bulge, the distance determinations are complicated by the heavy and patchy extinction. Fortunately, Stanek[40] derived maps of the projected extinction A_V and reddening E_{V-I} on the basis of Red Clump giants in the Bulge. These can be taken as maximum values of extinction and reddening, and then used in an iterative scheme, by assuming: $E_{V-I} = E_{V-I}^{max} \times d/d_0$ and $A_I = A_I^{max} \times d/d_0$, where d_0 measures the effective thickness of the dust disk, and where the distance is determined from $d = 10^{I-M_I+5-A_I}$. There are indications that d_0 is moderate ([2] [26] [25]). For the lower limit of $d_0 \simeq 2$ kpc, and for $b \simeq -4^\circ$, the total thickness of the dust layer would be about 300 pc. To see the sensitivity of the results, the other extreme of $d_0 = 8$ kpc was also considered and found less likely.

Figure 7 shows the period – distance plot. Why do we see a relation between these quantities? In principle, the two quantities should not correlate as – barring really unusual and then extremely-interesting astrophysical causes – the detection rate should be the same at all distances for a given period. It appears that the curved cutoff in the distribution of distant systems can be explained entirely by the existence of the short-period/blue envelope of the period–color relation. In order to be visible from large distances, a system must be blue and must have a long period which is impossible.

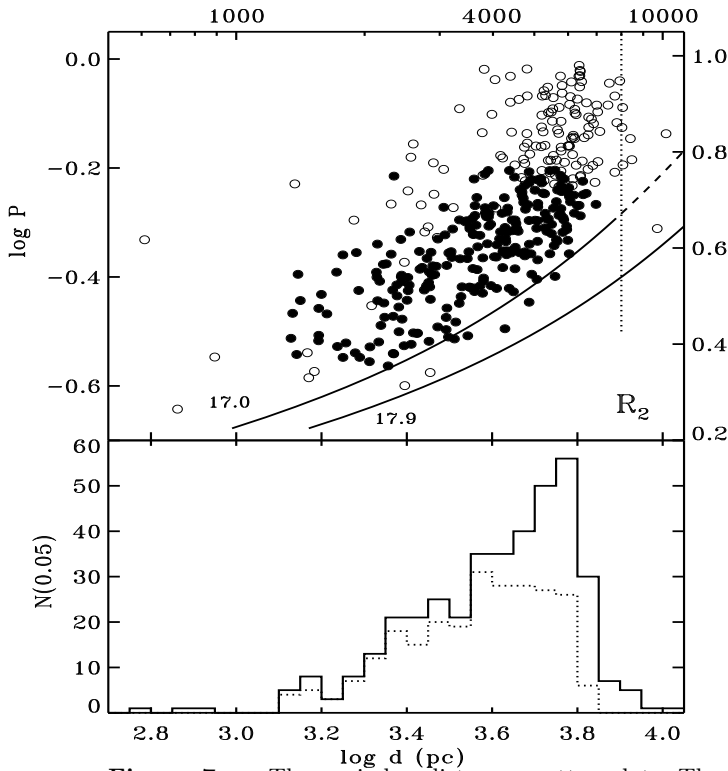


Figure 7. The period – distance scatter plot. The cutoff at large distances and short periods is entirely due to the existence of the short-period envelope in the PC relation.

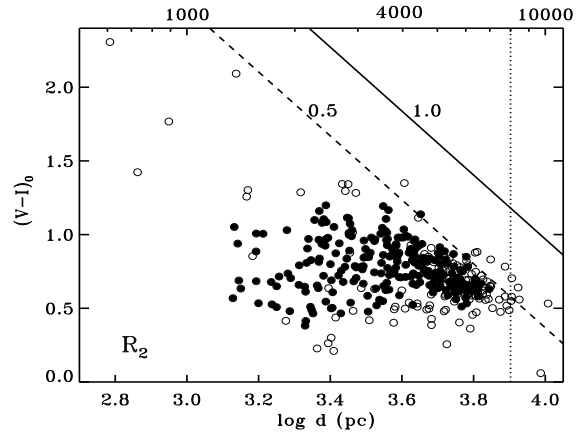


Figure 8. The intrinsic colours of contact systems are concentrated not far from those of the Turn-Off Point stars. In this figure, as in Figure 7, the filled and open circles mark those contact systems which fall within and outside the ranges of the strict applicability of the absolute-magnitude calibration. The continuous lines give the expected limits due to the final depth of the sample ($I \simeq 17.9$) and the two other relevant constraints: the short-period envelope (Fig. 7) and the conventional limit on the period of one day (Fig. 8; the line of 0.5 day is shown by a broken line). The vertical dotted lines in both figures mark $d = 8$ kpc, the expected distance to the Galactic Bulge. The results shown here are for $d_0 = 2$ kpc, which is symbolically denoted as R_2 .

By comparing the number of stars analysed for variability with the number of detected W UMa-type

systems, one can establish the relative frequency of occurrence. It is high. The apparent frequency, estimated to the distances of 2 and 3 kpc, equals to one contact system per about 250 – 300 Main Sequence stars. This estimate, with an approximate correction for undetected, low-inclination systems, leads to the spatial frequency of about $1/125 - 1/150$.

One can also simply count the contact binaries in the two volumes and find the spatial density. It is basically independent whether we count to 2 or 3 kpc (indicating a well-defined faint cutoff of the luminosity function) and equals about $(1.5 - 2.0) \times 10^{-4}$ per cubic parsec. This estimate is consistent with the frequency given above.

Having reddening for individual systems, we can ask about intrinsic colours of the systems (Fig. 8). They are confined to a relatively narrow range of $0.4 < (V - I)_0 < 1.0$. This enhancement in the colour distribution is reminiscent of the one observed in the CMD's of the stellar field in the range $0.4 < (V - I)_0 < 0.7$, which is explained by the “vertical” evolution in the TOP region of very old stars ([10] [27]). W UMa systems are probably not as old as Halo or Extended/Thick Disk populations as their numbers are simply too large. The Thick Disk contributes some 2% of all stars in solar vicinity; the spatial density of contact binaries of about $1/150$ or 0.7%, which would require that a large fraction of these old stars were contact binaries. A much more likely parent population of the contact systems is the Old Disk.

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